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A STUDY OF THE SO-CALLED "OVERREDUCED" CONDITION IN MOLTEN STEEL

By J. V. McCrae,[1] R. L. Dowdell, and Louis Jordan

ABSTRACT

A study was made of four heats of acid electric steel for castings in which two heats were in the so-called "overreduced" state while the others were in the normal condition as made according to general practice. The two types were investigated as regards temperature of the molten metal, structure, and physical and chemical properties.

The lower fluidity or "runability" of the overreduced (overdeoxidized) steel manifests itself in a short "filming-over time" with the melters' spoon test. This is apparently caused by the rapid formation of silica, which rises from the steel because of the addition of excess metallic silicon to an oxidized steel. This phenomenon may also be the cause of incorrect judgment of its temperature, since its emissivity is higher than that of a clean liquid steel surface.

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I. INTRODUCTION

This investigation of the so-called "overreduced" condition in acid steel as made in the electric furnace for castings was undertaken by the National Bureau of Standards in cooperation with The Steel Castings Development Bureau and followed the conclusion of the major phases of an earlier cooperative program on the cause of low ductility in certain plain carbon steel castings.[2]

It appeared probable that the two investigations might supplement each other to some extent. The overreduced condition has been said to result from, or be accompanied by, an excess of silicon or other strongly reducing agent in the liquid steel. The results of the earlier investigation on low ductility pointed to aluminum, also a strong reducing agent which was added to the liquid steel at the time of

[1] Deceased. Formerly research associate of Steel Castings Development Bureau.

[2] J. V. McCrae and R. L. Dowdell, Preliminary Studies of the Effect of Deoxidation and Mold Conditions on the Tensile Properties of Carbon Steel Castings, B. S. Jour. Research, 5; August, 1930.

casting, as the immediate cause of low ductility. Hence it was not an unreasonable conjecture that some relation might exist between the overreduced condition in the liquid steel and low ductility in the finished castings.

The work here reported has profited throughout from the interest, experience, and suggestions of George Batty, director of research of The Steel Castings Development Bureau.

II. "OVERREDUCED" STEEL IN PREVIOUS INVESTIGATIONS

In the conference at which this problem was suggested for study at the bureau, an overreduced steel was described by Mr. Batty as possessing a low fluidity which can, however, be remedied by a suitable addition of iron ore to the bath. Hence, a steel in an unsatisfactory condition is improved by oxidation and the unsatisfactory state is more or less logically designated as "overreduced."

The steel melter's test for fluidity in such cases has usually been to determine the time, in seconds, required for a film to form across the top surface of a sample of the molten steel poured into a standard open-core sand mold. A "fluidity count" of about 30 seconds may be obtained for an overreduced steel. After the addition of from 3 to 4 pounds of iron ore for a 4,000 to 5,000 pound heat, followed by an interval of about two minutes, the same steel might require about 48 seconds to film over. This filming test or fluidity count appears to serve as a practical guide to the running qualities of the metal and experience has shown that a metal having a short count gives trouble in filling satisfactorily thin sections of castings.

There are in the literature relatively few papers bearing on the subject of overreduced steels. Melmoth,[3] has mentioned briefly in several papers the comparative fluidity of steels for castings. In one of these papers he suggested that "fluidity may not be a direct function of temperature and orthodox composition," and goes on to affirm his belief in the difference in fluidity or "life" which is reported to exist between electric and converter steels of similar composition. Greater fluidity of steel made by the converter process has been attributed to the presence of oxides which continue to react with deoxidizers during the period of casting with a consequent production of heat. This theory is to be questioned since no serious loss of deoxidizing elements during casting periods is encountered in practice. A second theory was that dissolved oxygen or oxides lowered the solidification temperature of the steel and so gave a longer liquid range.

In the discussion of the above paper, Batty was of the opinion that an overreduced steel bath was one comparatively free from iron oxides. The general English practice was to add sufficient silicon, after the oxidizing slag had been removed, to deoxidize the bath and to leave about 0.10 per cent silicon in the steel. In their basic practice, additions of carbon were made to the slag so that some of the silicon would be derived from the slag by reduction. In a steel overreduced in this manner, it was mentioned that not only was the

[3] F. A. Melmoth, Some Metallurgical Points in Electric Steel Castings and Notes on Defects, Inst. British Foundrymen, 9, p. 425; 1925–26.

fluidity lowered, but there resulted also greater shrinkage, more susceptibility to the effects of gases from the mold, and a greater tendency to porosity. The increased shrinkage was apparent in both the fluid condition and in the solidified condition and called for the use of larger heads or risers and a greater allowance in the pattern for contraction in order that the casting might conform to proper dimensions.

Batty cited an instance of an electric furnace heat of 5,000 pounds which, although very hot, gave a "melter's count" of not more than 22 seconds. The slag samples were whitish in color, indicative of a strongly "reduced" condition, and not greenish. To this charge about 100 pounds of rusty plate scrap (plates one-half inch thick) were added and rapidly melted. Within 2 minutes a spoon sample showed a "melter's count" of between 48 and 51 seconds. He stated that this heat could not have been poured from hand shanks had it been tapped in the overreduced condition.

In the discussion of the same paper, G. C. Grant supported Batty's remarks and stated that a small percentage of titanium had a similar effect in bringing a hot heat, which normally would have run without difficulty through a three-fourths-inch nozzle, to a condition in which it was poured from the ladle only with difficulty.

In discussing a paper by Dornin,[4] Batty stated that McCance had noted a peculiar phenomenon in that high-chromium steels and high-silicon steels on casting appeared to give up a considerable proportion of their surface heat as light. In the bottom pouring of ingots certain of these steels run short, due to a freezing of the metal on the surface in the molds during casting and thus develop a back pressure greater than the ferrostatic pressure of the superimposed metal in the trumpet.

Batty also stated that overreduced mild steels from basic electric furnaces are very sluggish in the molds and are somewhat of a menace in the production of light steel castings. He also expressed the opinion that dissolved oxide of iron is an essential to fluidity in low-carbon steels, and that overreduced heats had been cured by adding oxide of iron in various forms, such as rusty scrap, finely divided ore, or mill scale. If the heat is "hot," rusty scrap is the best addition to lower the temperature; if the heat is close to the correct temperature, mill scale or ore makes the better addition. Mill scale in any appreciable quantity is undesirable because of the high sulphur content. Batty further stated that he preferred to call a steel which was assumed to contain some unknown proportion of this dissolved oxide a normal steel. He also mentioned that such a metal had a finer grain size than that obtained with an overreduced steel of the same general composition and that the normal steel also machined more readily although it had a somewhat higher Brinell hardness than the overreduced type.

In a later paper Melmoth[5] states that:

> Over a very large number of electric furnace casts it is strongly suggested that abnormally high silicon produces a material much more difficult to cast from small shanks than when silicon content is normal. The principal point observed is the tendency to skin over on the surface of the metal immediately after it is

[4] G. A. Dornin, "The Melting or Molten Stage of Steel Manufacture, with Particular Reference to the Deoxidizing, Refining, and Contamination Phases," Trans. Am. Soc. Steel Treat., 13, p. 29; 1928.
[5] F. A. Melmoth, Sheffield, England, "Variables in Steel Foundry Practice," Trans. Am. Fdymen's. Assoc., 36, p. 323; 1929. Exchange paper with Institute of British Foundrymen.

exposed to the air. It appears incorrect to state dogmatically that this is due to the direct action of the presence of silicon, as it may equally be due the furnace condition which tended toward the production of the silicon content. These charges are frequently very dead and result from strongly reducing conditions. Even when hot they do not exhibit the usual degree of fluidity and have been termed "dazed" heats. The condition is remediable by a return to oxidizing conditions in the furnace, afterwards finishing as usual.

III. COMPARISON OF OVERREDUCED AND NORMAL STEEL

The present investigation consisted of a comparison of the melting practice, the mechanical properties, and the chemical composition of the two heats of intentionally overreduced acid electric steel, and two heats of similar steel made according to normal practice. The overreduced heats are designated in this report as heats 6698 and 6699 while the normal heats are 6704 and 6705.

All four heats are made at the plant of the Dodge Steel Co., one of the cooperating foundries of The Steel Castings Development Bureau. Grateful acknowledgment is made of this assistance rendered by the Dodge Steel Co., particularly the personal interest in the supervision of the heats by C. Tolan and C. S. Roberts. Thanks are also due and are gladly rendered to Dr. C. H. Herty, jr., and J. M. Gaines, jr., of the Bureau of Mines, Dr. R. B. Sosman, of the U. S. Steel Corporation; George Batty, of The Steel Castings Development Bureau; and H. J. French, formerly of the National Bureau of Standards, for their aid in observing and recording data during the four heats in question. All temperature measurements during the heats under consideration were made by H. T. Wensel and W. F. Roeser, of the National Bureau of Standards.

1. MELTING PRACTICE

The detailed data showing the melting practice are given in Table 1 for the two normal heats and in Table 2 for the two overreduced heats.

TABLE 1.—*Melting practice for the "normal" acid electric steels*

HEAT 6704. FURNACE CHARGE: SHOP SCRAP, 2,000 POUNDS; BOILER PUNCHINGS, 3,000 POUNDS; IRON ORE, 80 POUNDS

Time of operation	Furnace operation	Power consumption	Specimen designation	Furnace additions		Indicated fluidity			Temperature	Chemical composition						
				Material	Amount	Melters count	Cone altitude	Spiral length		Slag			Metal			
										FeO	MnO	SiO_2	C	Si	Mn	Al
		kwh			*Pounds*	*Seconds*	*cm*	*cm*	*° C.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Per cent*
11.30 a. m.	Power on															
12.30 p. m.	Melt down	910														
12.35 p. m.			A							25.8	23.4	48.2				
12.41 p. m.				Lime	4											
12.57 p. m.		1,315	B	Iron ore	4		2	18	1,607	29.7	18.4	49.8	0.12	0.07	0.10	
1 p. m.				Wash metal	40											
1.05 p. m.				do	60											
1.09 p. m.		1,440	C			52	30	35	1,675	19.0	14.7	63.2	.14	.05	.10	
1.12 p. m.				Wash metal	30											
1.14 p. m.	Poled with steel rod.															
1.17 p. m.						59										
1.17.30 p. m.				(50 per cent Si) ferro silicon.	40											
1.20 p. m.				(80 per cent Mn) ferro manganese.	55											
1.21.30 p. m.		1,590	D			30	0	23	1,710	12.9	13.0	72.9	.25	.40	.99	
1.25 p. m.	Power off (tapped)	1,620	F						1,720							
1.30 p. m.	Start of pour		T_1 TA_1, TA_2	Aluminum	1 lb./ton in shank ladle.								.25	.37	.69	Not detected. 0.011.

TABLE 1.—*Melting practice for the "normal" acid electric steels*—Continued

HEAT 6705. FURNACE CHARGE: SHOP SCRAP, 2,000 POUNDS; BOILER PUNCHINGS, 3,000 POUNDS; IRON ORE, 40 POUNDS

Time of operation	Furnace operation	Power consumption	Specimen designation	Furnace additions		Indicated fluidity			Temperature	Chemical composition						
				Material	Amount	Melters count	Cone altitude	Spiral length		Slag			Metal			
										FeO	MnO	SiO_2	C	Si	Mn	Al
		kwh			*Pounds*	*Seconds*	*cm*	*cm*	*° C.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Per cent*
1.38 p. m.	Power on															
2.50 p. m.	Melt down	980								22.6	16.0	59.9				
2.57 p. m.			A													
3.04 p. m.				Lime	4											
3.07 p. m.				Iron ore	15											
3.14 p. m.													[1] 0.14			
3.16 p. m.			B			48	1	12		22.6	16.2	60.3	.10	0.08	0.11	
3.19 p. m.				Wash metal	40											
3.23 p. m.				do	10											
3.29 p. m.			C			72	4	50	1,571	19.4	17.4	61.5	.08	.08	.12	
3.32 p. m.				(50 per cent Si) ferro silicon.	35				1,643							
3.34 p. m.				(80 per cent Mn) ferro manganese.	55				1,668							
3.33 p. m.	Power off	1,590	D			48	29	55	1,690	12.9	8.6	77.6	.20	.37	.77	
3.37 p. m.	Tapped															
3.40 p. m.	Start of pour		F				3	17	1,647				.20	.38	.72	
			T_1, T_2													0.005.
			TA_1, TA_2	Aluminum	1 lb./ton in shank ladle.								.19	.35	.73	.021.

[1] Estimated.

TABLE 2.—*Melting practice for the "overreduced" acid electric steels*

HEAT 6698. FURNACE CHARGE: SHOP SCRAP, 2,000 POUNDS; BOILER PUNCHINGS, 3,000 POUNDS; IRON ORE, 30 POUNDS

Time of operation	Furnace operation	Power consumption	Specimen designation	Furnace additions		Indicated fluidity			Temperature	Chemical composition						
				Material	Amount	Melters count	Cone altitude	Spiral length		Slag			Metal			
										FeO	MnO	SiO_2	C	Si	Mn	Al
		kwh			*Pounds*	*Seconds*	*cm*	*cm*	° *C.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Per cent*
11.50 a. m.	Power on															
12.50 p. m.	Melt down	920														
12.53 p. m.			A							14.2	24.8	58.2	0.27	0.12	0.21	
1.04 p. m.				Iron ore	18											
1.06 p. m.				Lime	4											
1.12 p. m.				Iron ore	10											
1.15 p. m.				do	10											
1.25 p. m.			B			43	1	5		20.0	17.1	60.5	.24	.08	.12	
1.27 p. m.				(50 per cent Si) ferro-silicon.	15											
1.32 p. m.				do	5				1,563							
1.41 p. m.			C			33	30	35	1,574	15.9	13.9	69.0	.12	.16	.20	
1.43 p. m.		1,540							1,573							
1.44 p. m.				Iron ore	7				1,574							
1.50 p. m.			D	(80 per cent Mn) ferro-manganese.	52	43	30	38	1,610				.27	.34	1.07	
1.52 p. m.									1,635							
1.54 p. m.			E				30	40	1,660				.24	.34	.60	
1.55 p. m.	Tapped	1,570							1,720							
2 p. m.	Start of pour								1,617							
2.06 p. m.									1,590							
			F				3	18					.22	.40	.72	
			T_1, T_2						1,555							0.005
2.08 p. m.			TA_1, TA_2	Aluminum	1 lb./ton in shank ladle.				1,543							.027

TABLE 2.—*Melting practice for the "overreduced" acid electric steels*—Continued

HEAT 6699. FURNACE CHARGE: SHOP SCRAP, 2,000 POUNDS; BOILER PUNCHINGS, 3,000 POUNDS; IRON ORE, NONE

Time of operation	Furnace operation	Power Consumption	Specimen designation	Furnace additions		Indicated fluidity			Temperature	Chemical composition						
				Material	Amount	Melters count	Cone Altitude	Spiral length		Slag			Metal			
										FeO	MnO	SiO_2	C	Si	Mn	Al
		kwh			*Pounds*	*Seconds*	*cm*	*cm*	*° C.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Per cent*
2.08 p. m.	Power on															
3.17 p. m.	Melt down	1,000								23.2	21.9	52.9		0.06	0.12	
3.24 p. m.			A	Iron ore	20											
3.28 p. m.				Lime	4				1,573							
3.40 p. m.							½	38	1,656	14.9	10.1	74.1	0.30	.04	.20	
3.54 p. m.			B													
						70			1,664							
3.56 p. m.		1,400		(50 per cent Si) ferrosilicon.	20				1,671							
3.58 p. m.				do	10				1,696							
4.09 p. m.						41			1,700							
4.13 p. m.						34	30	50	1,703	15.5	11.8	72.1	.16	.28	.20	
4.15 p. m.		1,550	C			36			1,707							
4.19 p. m.		1,580		(80 per cent Mn) ferromanganese.	55											
									1,710							
4.22 p. m.						31		0	1,710	14.8	12.5	70.8	.26	.32	1.06	
4.24 p. m.		1,610	D				½	0	1,710				.27	.33	.73	
4.25 p. m.			E													
4.26 p. m.	Power off															
4.26.20 p.m.	Tapped															
4.30 p. m.	Start of pour								1,594							
4.37 p. m.																
4.38 p. m.			F						1,525							Not detected.
			T_1, T_2						1,533							0.022
4.38 p. m.			TA_1, TA_2	Aluminum	1 lb./ton in shank ladle.											

The two normal heats contained iron ore in the original charge to the amount of 80 pounds in the first heat and 40 pounds in the second. Shortly after the "melting down" of the first heat a further small addition of ore (4 pounds) was made. Three successive additions of "wash metal," totaling 130 pounds, were made from 30 to 45 minutes after the melt down and additions of ferrosilicon and ferromanganese before tapping. The second normal heat was made much the same as the first, but with a slightly larger addition of iron ore (15 pounds) after the melt down and with only 50 pounds of wash metal.

Of the two overreduced heats, the first had only 30 pounds of ore in the furnace charge while the second charge contained no ore. Additions of 38 and 20 pounds of iron ore were made to these two heats, respectively, shortly after the melt down. Wash metal was not added to these two overreduced heats. The steel in the furnace was, instead, deoxidized directly by the usual additions of ferrosilicon and ferromanganese.

Samples of both metal and slag were taken as indicated in Tables 1 and 2. The "A" samples were taken immediately after the charges melted down, the "B" samples after the furnance additions of ore and lime were completed; the "C" samples followed the deoxidizing additions, respectively—wash metal in the normal heats and ferrosilicon in the overreduced heats. The "D" samples were taken immediately before tapping. It is to be noted that between the "C" and "D" samples additions of both ferrosilicon and ferromanganese were made in the two normal heats, while in the overreduced heats only ferromanganese was added between "C" and "D" samples. Additional fluidity test samples ("E") were taken from the heats just before tapping while the "F" samples were taken immediately after the start of the pour.

The samples marked "T" and "TA" represent sand-cast test blocks of the finished steel poured from the ladle, the "T" samples representing the finished steel with no ladle addition and the "TA" samples metal to which aluminum in the proportion of 1 pound per ton had been added in a 70-pound shank ladle.

2. TEMPERATURE MEASUREMENTS

The temperature measurements at various stages of the heats are recorded in Tables 1 and 2. The records of temperature during one each of the normal and overreduced heats are shown in Figures 1 and 2.

It was originally planned to make the temperature measurements with noble metal thermocouples and preliminary tests were made at the National Bureau of Standards with commercial alundum protection tubes. These proved unsatisfactory, both because of their sensitiveness to thermal shock and also because of the ease with which they were attacked by acid slags so that they were readily cut through at the slag line. A very few temperature measurements were made with a noble metal thermocouple with a porcelain protection tube next to the couple and an outer clay-graphite tube to protect the porcelain. All other temperature measurements shown by the two figures represent optical pyrometer readings.

The temperature measurements in the furnace were made by sighting the optical pyrometer into a clay-graphite tube inserted through a hole in the furnace wall just above the slag line. The clay-graphite tube was inserted at an angle of 45° to the horizontal, and extended through the slag layer into the metal bath. These tubes were 36 inches long with a bore of seven-eighths inch and a wall thickness of one-half inch.

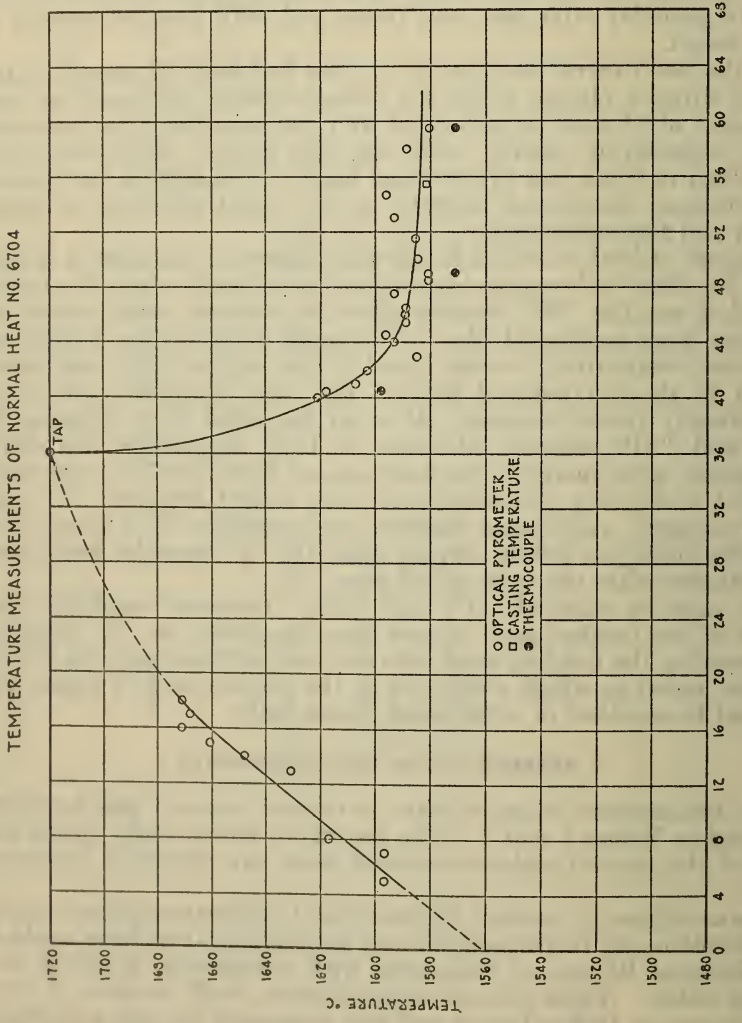

FIGURE 1.—*Temperature measurements on normal heat 6704*

The temperature of tapping was measured by sighting the optical pyrometer on the stream of metal flowing into the large (5,000-pound) ladle. The apparent temperature thus obtained was corrected for an emissivity of 0.40.[6] The temperatures of the steel subsequent to tapping were measured by sighting the optical pyrometer on the stream of metal flowing from the large ladle into the casting ladles and again

[6] G. K. Burgess, B. S. Tech. Paper No. 91; 1917.

applying the correction for an emissivity of 0.40. The correctness of these readings was checked in the case of another heat (6703), by simultaneous measurements with thermocouples in the 5,000-pound ladle and with the optical pyrometer on the stream flowing from the same ladle. Also in heat No. 6704 (fig. 1) thermocouple temperature readings were taken of the metal in the casting (250-pound) ladles while at the same time readings with the optical pyrometer were made

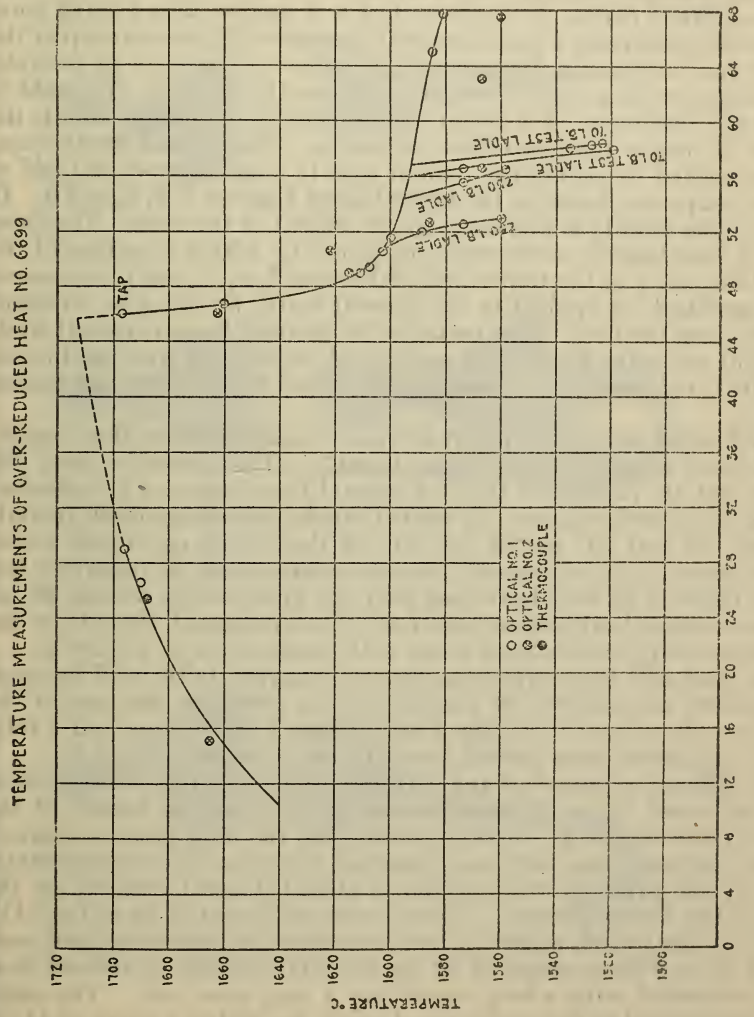

FIGURE 2.—*Temperature measurements on overreduced heat 6699*

on the stream of metal flowing from the 5,000-pound ladle into the 250-pound ladle. The temperature of the metal in the smaller ladle was found to be slightly lower than the temperature of the stream of metal filling the ladle, a condition which was to be expected.

The temperature data obtained do not show any significant differences between the normal and the overreduced heats. The rate of cooling of the metal in the 5,000-pound ladle was nearly the same in

all four heats, and the temperature of the metal became approximately constant in all cases at 1,580° to 1,600° C. during the casting period.

3. FLUIDITY TESTS

A reliable method for the determination of the fluidity of low-carbon steel has long been a problem with steel-foundry men. There is no standard or generally accepted test method. In this work three different types of "fluidity" test were used. In the first method, known as the melter's count, the molten steel was poured into a small core-sand mold containing a hemispherical depression 2½ inches deep at the center and with a top diameter of 3½ inches. The time in seconds, as measured with a stop watch, required for the metal in this mold to freeze or "film over" was taken as the melter's or fluidity count, the longer the count the more fluid the metal. The second fluidity test used consisted in casting the molten steel in a split core-sand mold of conical shape, as shown in the lower half of Figures 3, 4, 5, and 6. In this test the fluidity is indicated by the height of the cone. The third type of test, known as the spiral method,[7] by which a casting of the form illustrated in the upper half of Figures 3, 4, 5, and 6 was somewhat modified, as applied in the present work, by using an overflow so as to keep the head of the metal in the pouring basin constant while the mold was being filled. The sand molds were made from split cores. Fluidity is indicated by the length of the spiral traversed by the molten steel.

The fluidity tests were taken at various stages during the progress of the heats as indicated in Tables 1 and 2. The melter's counts (52, 59, 30 and 48, 72, 48) on the two normal heats indicate a somewhat greater fluidity throughout the heats than do the corresponding counts (43, 33, 43 and 70, 41, 34, 36, 31) of the two overreduced heats. Nevertheless, it is to be noted that the counts were all relatively low at the finish of all four heats and that the final counts, 30 and 48, on the two normal heats did not serve at all to distinguish them from the two supposedly overreduced heats with final counts of 43 and 31.

The cone and the spiral tests generally agreed fairly well between themselves, as is shown by Figures 3 to 6, except in the case of the "C" sample of heat 6705 (fig. 4 (*c*)), where a short cone and a relatively long spiral were poured from the same metal.

It is difficult to point out any correlation between the melter's count and the other types of fluidity tests throughout the course of the heats. However, it is worthy of note that the final furnace samples of the cone and spiral tests corresponded with what the original statement of the problem of overreduced steel led one to expect on the basis of the melter's count. Thus, a melter's count of 30 at the "D" sample of heat 6704, a normal heat, ran short in both spiral and cone (fig. 3 (*d*)); while a count of 48 for the "D" sample of normal heat 6705 compared with a long spiral and a long cone test. The same situation existed in the overreduced heats, the melter's count of 43 for heat 6698 matched the long cones and spirals of Figure 5 (*d*) and (*e*) and the short count 31 for heat 6699 compared with cone and spiral tests which showed practically no fluidity. (Fig. 6 (*e*).)

For the two heats which showed high counts and good fluidity in the casting tests, namely, normal heat 6705 and overreduced heat

[7] C. Curry, Fluidity Qualities of Cast Iron, Trans. Am. Fdy. Assoc., **35**, p. 289; 1927.

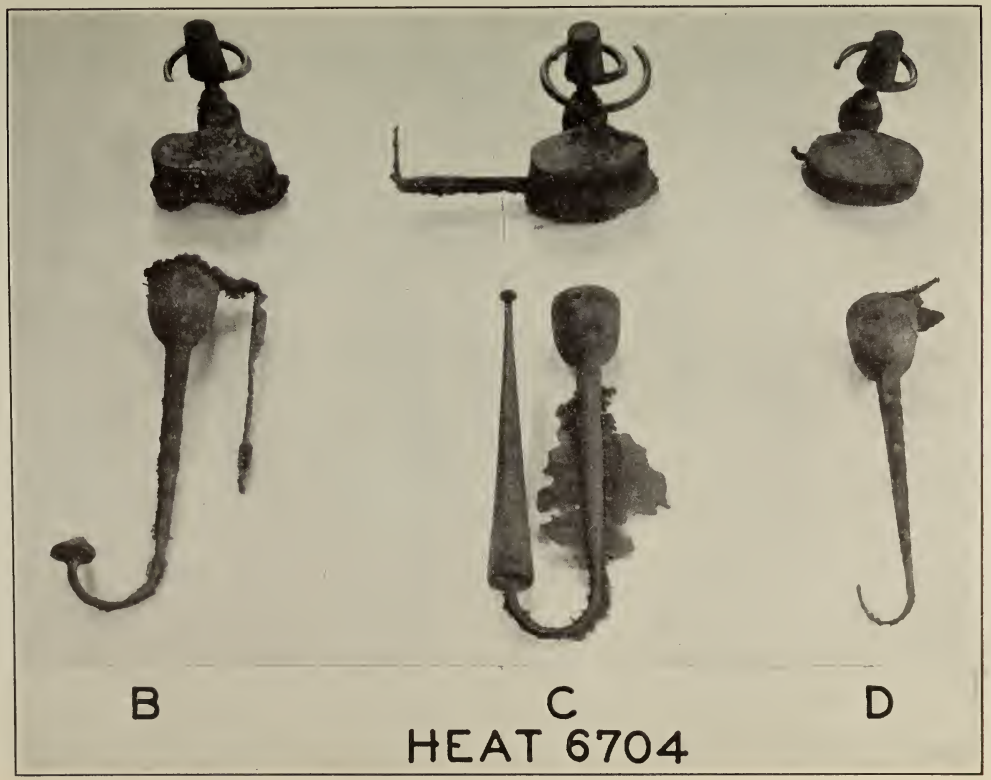

FIGURE 3.—*Fluidity test specimens of cone and spiral types from normal heat 6704*

Letters indicate the time at which the specimens were taken during the progress of the heat. (See Table 1.)

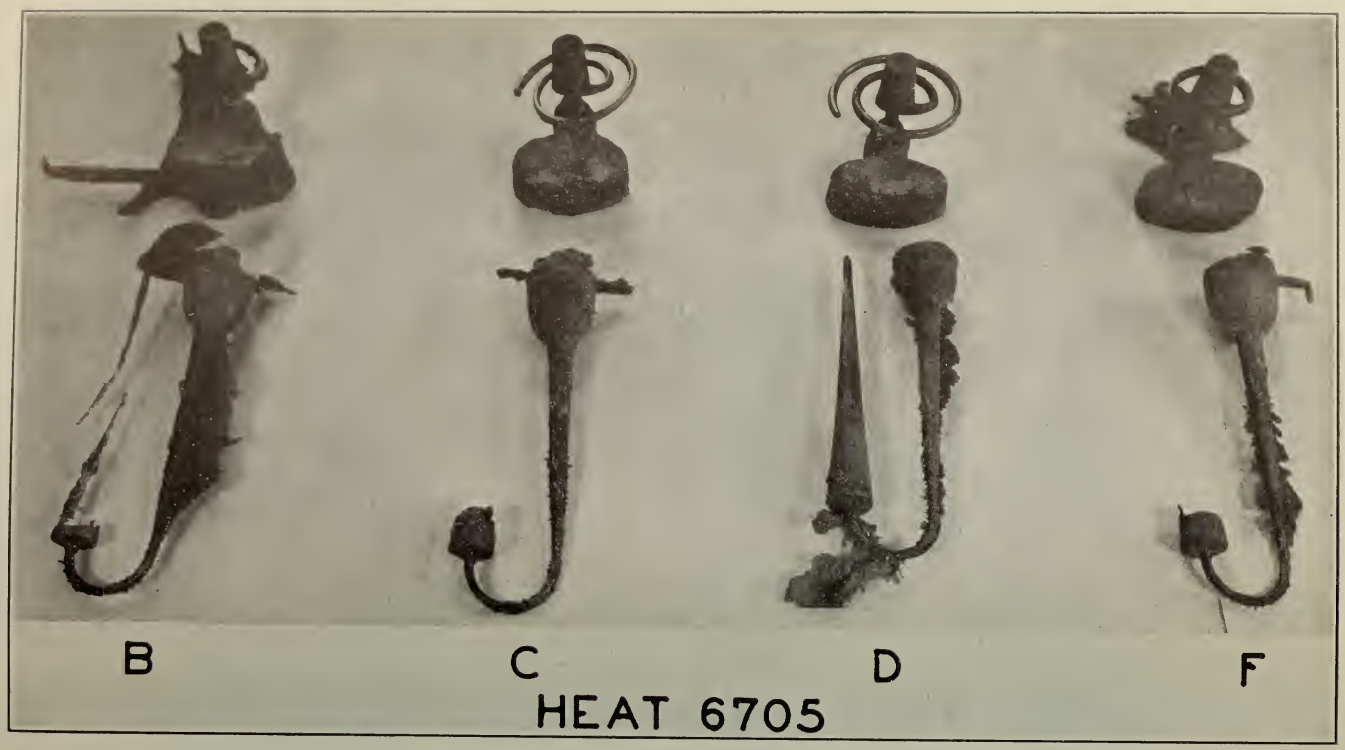

FIGURE 4.—*Fluidity test specimens of cone and spiral types from normal heat 6705*

Letters indicate the time at which the specimens were taken during the progress of the heat. (See Table 1.)

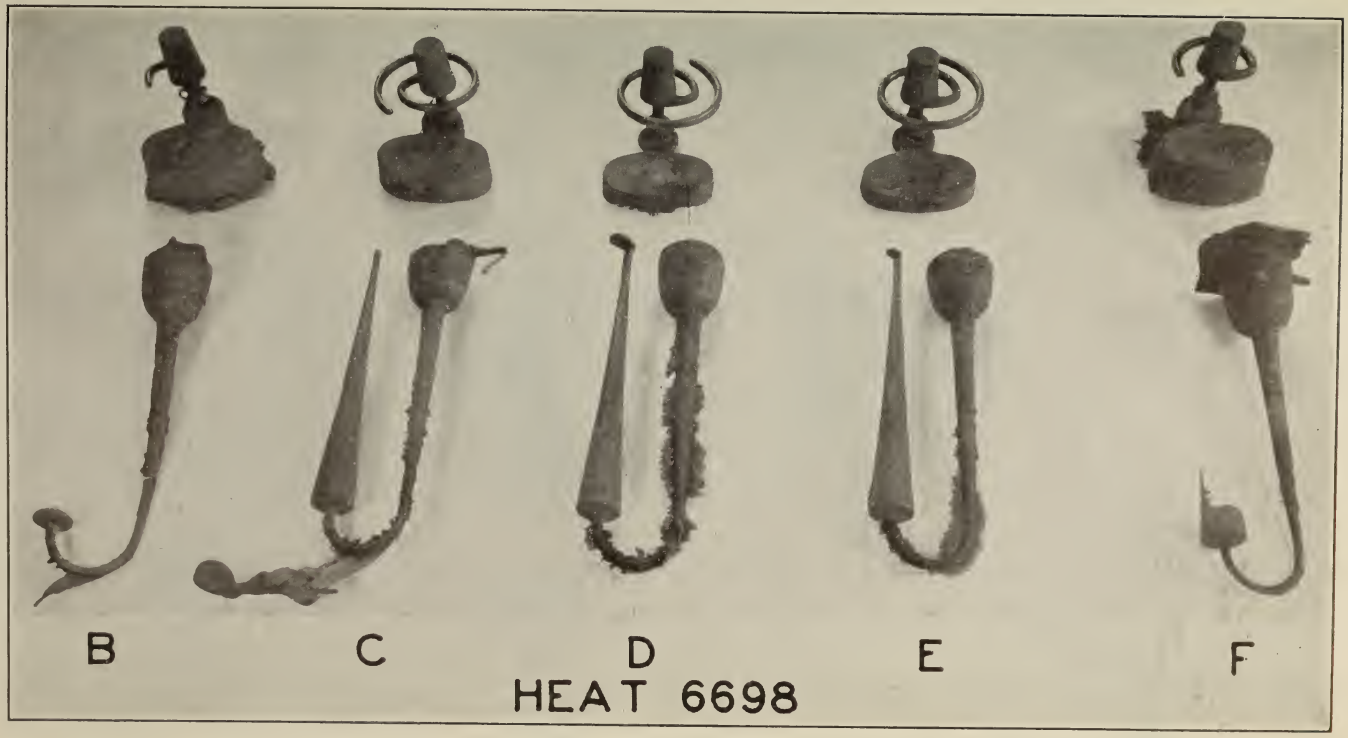

FIGURE 5.—*Fluidity test specimens of cone and spiral types from overreduced heat 6698*

Letters indicate the time at which the specimens were taken during the progress of the heat. (See Table 2.)

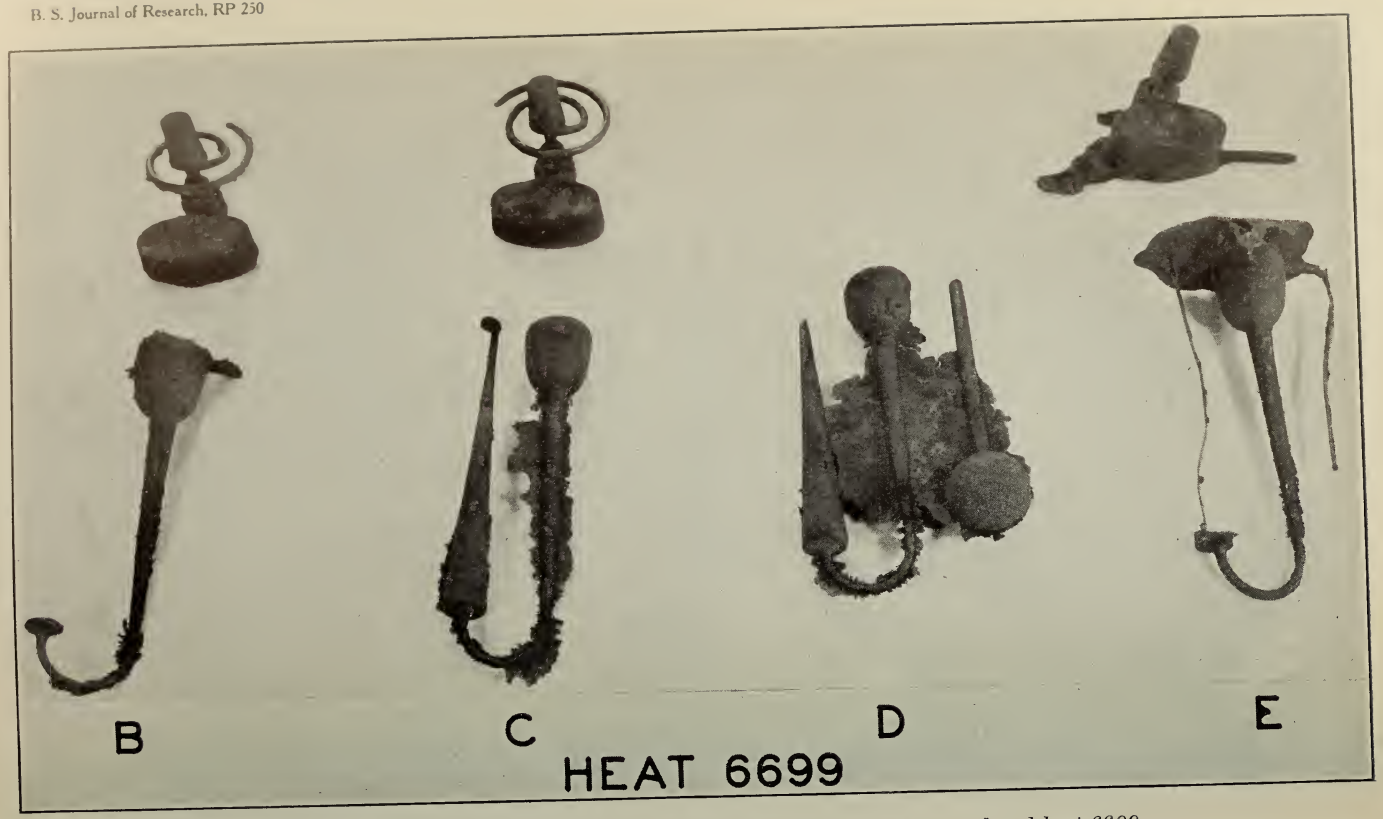

FIGURE 6.—*Fluidity test specimens of cone and spiral types from overreduced heat 6699*

Letters indicate the time at which the specimens were taken during the progress of the heat. (See Table 2.)

6698, there were also taken fluidity castings from ladle metal to which aluminum equivalent to 1 pound per ton was added in the hand shank. These were the F samples in Figures 4 and 5 and they indicate that aluminum additions in these proportions very noticeably lowered the fluidity possessed previously by the metal.

4. TENSILE PROPERTIES

Test bars of 0.505 inch diameter were made from test castings having the form and dimensions shown in Figure 7. In nearly all cases duplicate test castings were poured from each heat both without and with the addition of aluminum (1 pound per ton of steel, equivalent to 0.05 per cent Al.). The test castings were heat treated before the

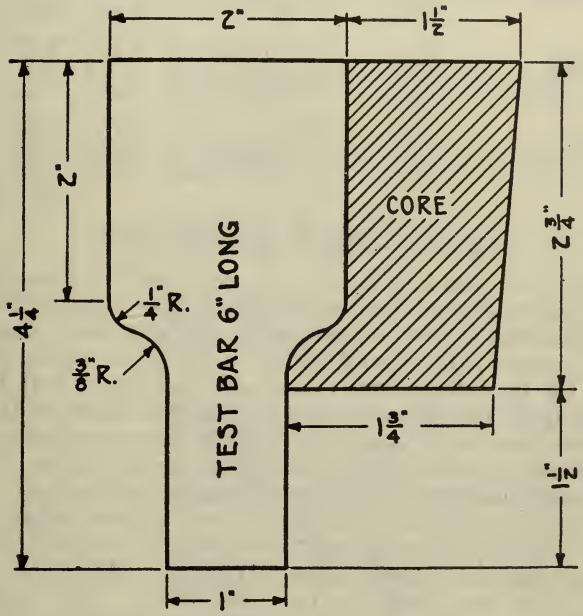

FIGURE 7.—*Form of test casting for tensile bars*
These bars were taken from the 1-inch section.

test bars were machined from them. The heat treatment consisted of normalizing by heating two hours at 900° C. (1,650° F.) in a large plant furnace, along with other castings, followed by air cooling.

All of the bars were sound except one bar, from heat 6704, that had been poured without the addition of aluminum. The results of the tensile properties given in Table 3 show that the bars deoxidized with aluminum in the shank ladle had considerably lower elongation and reduction of area than the corresponding bars from each heat which did not contain aluminum. This is the outstanding feature of the tensile tests and confirms the results of the earlier work on the cause of low ductility in acid electric casting steels, to which reference was made in the introduction of the present paper. There are no apparent

differences between the tensile properties of the normal and the overreduced heats. The broken tensile test bars are shown in Figure 8.

TABLE 3.—*Tensile properties of the normal and overreduced steels*

Heat No.	Specimen No.	Ladle addition	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area
			Lbs./in.²	*Lbs./in.²*	*Per cent*	*Per cent*
6704 (normal)	T_1	None	47,000	77,000	34.0	53.0
	T_2	do	Not tested because of porosity			
	TA_1	1 lb. Al/ton	49,000	75,000	24.0	30.0
	TA_2	do	50,000	73,000	15.0	20.0
6705 (normal)	T_1	None	44,500	72,500	34.0	55.5
	T_2	do	45,000	71,000	34.0	53.0
	TA_1	1 lb. Al/ton	46,000	71,000	27.5	26.5
	TA_2	do	44,000	66,500	25.5	32.0
6698 (overreduced)	T_1	None	46,500	76,500	32.5	50.5
	T_2	do	49,000	77,500	32.5	55.0
	TA_1	1 lb. Al/ton	47,000	73,500	23.0	28.0
	TA_2	do	49,000	74,000	27.0	36.5
6699 (overreduced)	T_1	None	50,500	79,000	32.4	52.5
	T_2	do	48,500	74,000	35.0	50.0
	TA_1	1 lb. Al/ton	51,000	77,000	26.5	32.5
	TA_2	do	50,000	76,500	21.0	27.0

5. MICROSCOPIC EXAMINATION

Specimens from the four heats were examined microscopically both in the etched and unetched conditions. The comparison of these structures for one of the normal and one of the overreduced heats is given in Figures 9, 10, 11, and 12 but is not discussed in detail. The specimens for the microscopic examination of the T and TA samples were taken from the threaded ends of the test bars, while the other samples were from water-quenched pellets (approximately one-fourth inch in diameter) obtained by pouring a spoon sample of the metal, freed from slag, through a heavy metal screen into water.

It was especially difficult to obtain micrographs showing the average inclusions for the different samples with a magnification of 100 diameters. With a magnification of only 25 diameters most of the inclusions were too small to be recognized. The "nonmetallic" inclusions in the unetched samples from the overreduced heats appear to be more finely divided than those in the normal heats. This is doubtless due to the presence of larger proportions of silica in the inclusions of the overreduced heats and as a result there has been less cleansing of this steel than in the case of the normal steel. With the normal practice there were apparently formed ferrous silicates higher in iron oxide which more readily agglomerated and rose to the slag.

In general, it was noted that the inclusions were darker after the ferrosilicon additions. This was apparently due to a higher concentration of silica in the inclusions which caused them to be more transparent, to appear darker under reflected light and to have a "bull's eye" appearance. (Fig. 11 (*A*)×100.) There is no appreciable difference between the unetched micrographs of the "T" and "TA" samples. There was a considerable difference in the ductility of steels with and without aluminum, but this difference in properties is apparently not caused by large particles of alumina.

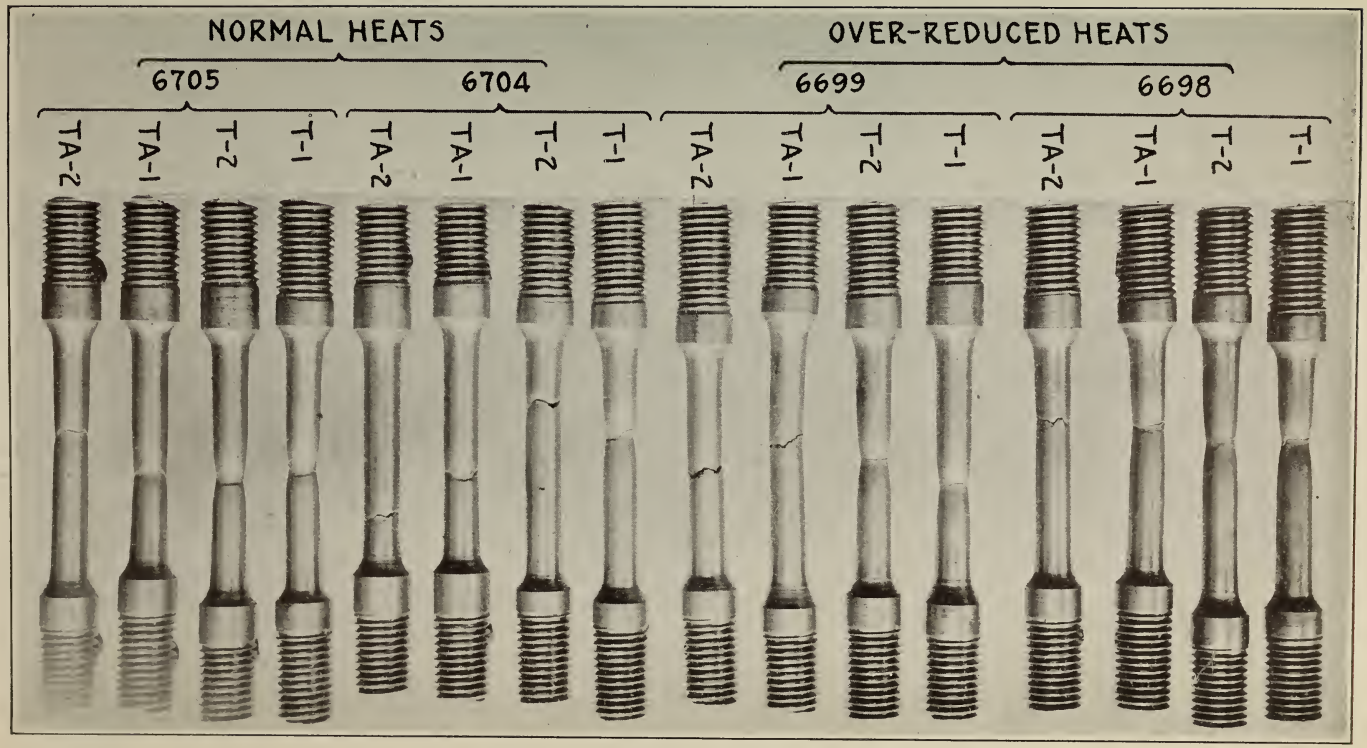

FIGURE 8.—*Broken tensile bars of all heats*

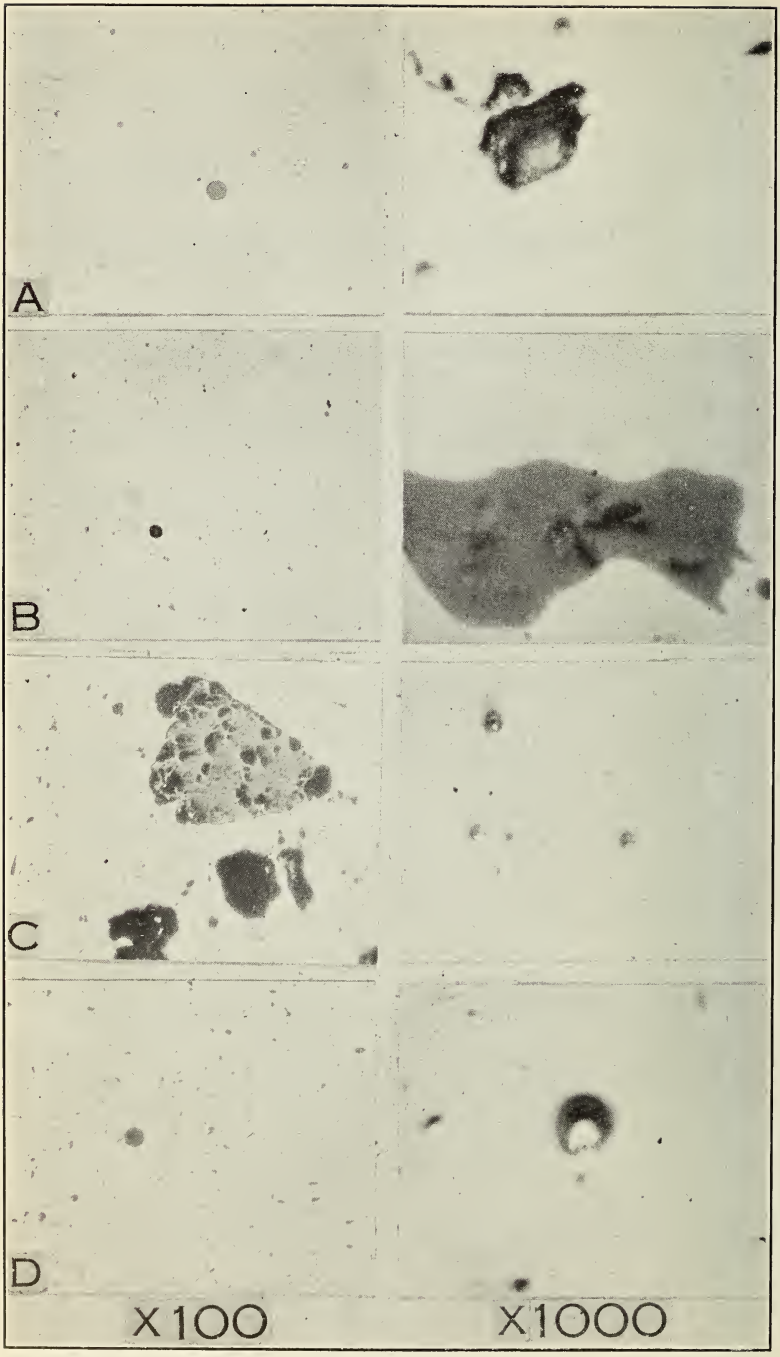

FIGURE 9.—*Inclusions in samples from normal heat 6705. Unetched condition*

Letters indicate the time at which samples were taken during the progress of the heat. (See Table 1.)

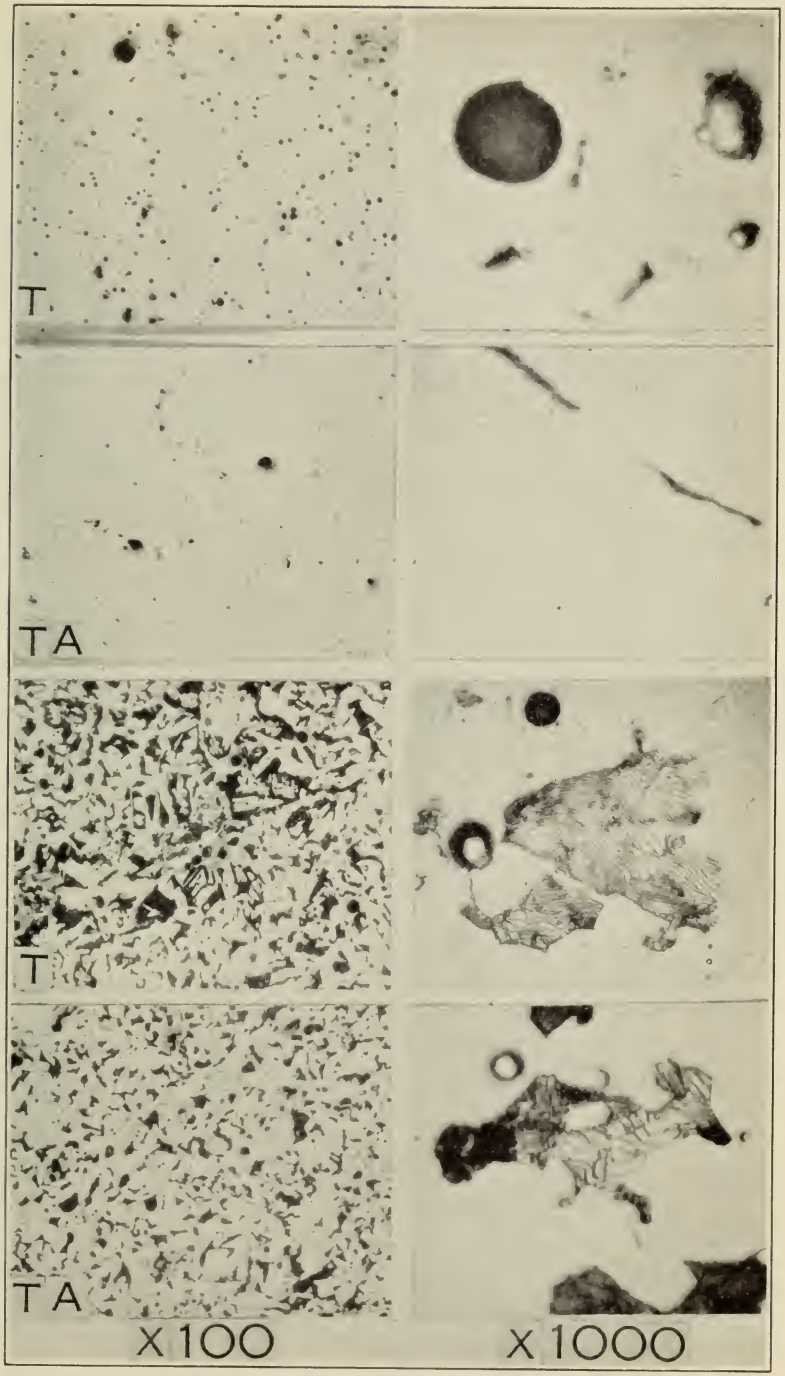

FIGURE 10.—*Inclusions in samples from normal heat 6705*

Letters indicate the time at which samples were taken during the progress of the heat. (See Table 1.) Specimens in upper half of figure in unetched condition. Specimens in lower half of figure etched in 2 per cent nital.

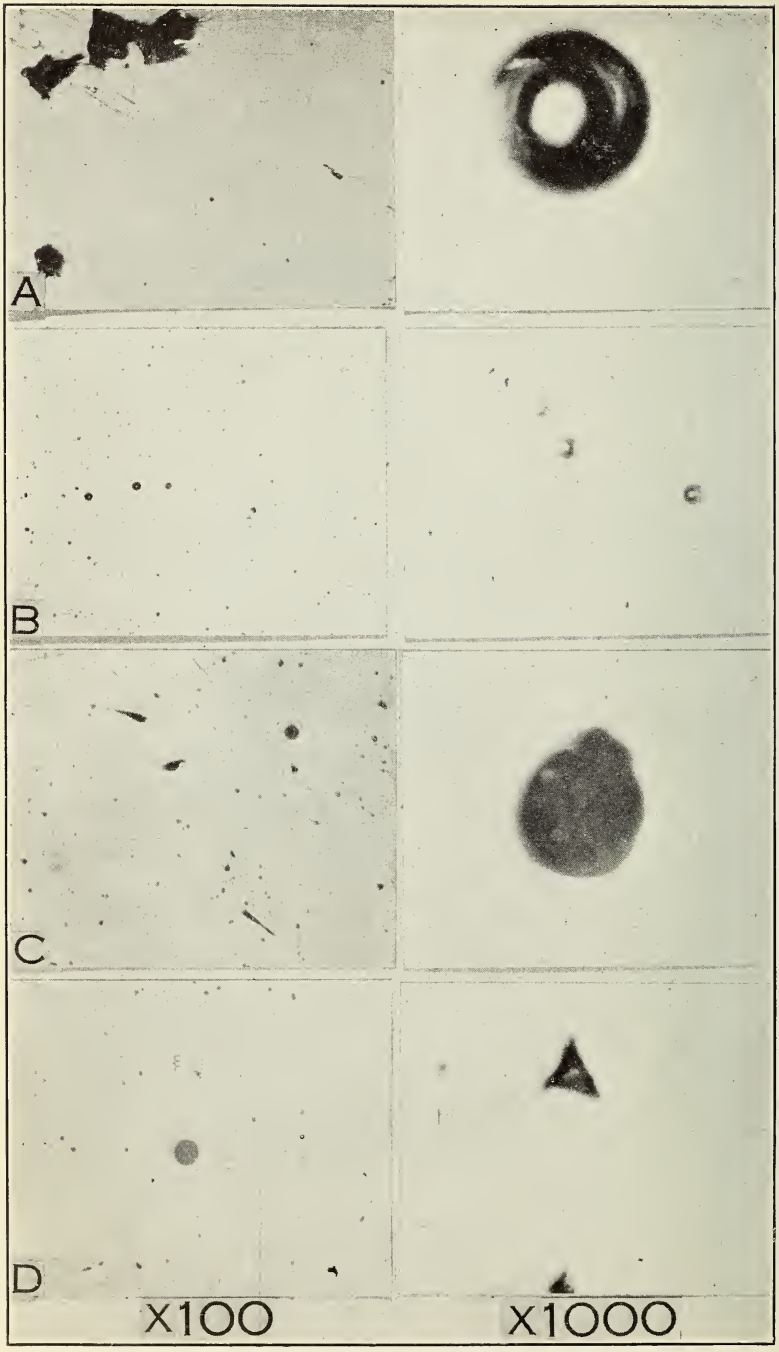

FIGURE 11.—*Inclusions in samples from overreduced heat 6699. Unetched condition*

Letters indicate the time at which samples were taken during the progress of the heat. (See Table 2.)

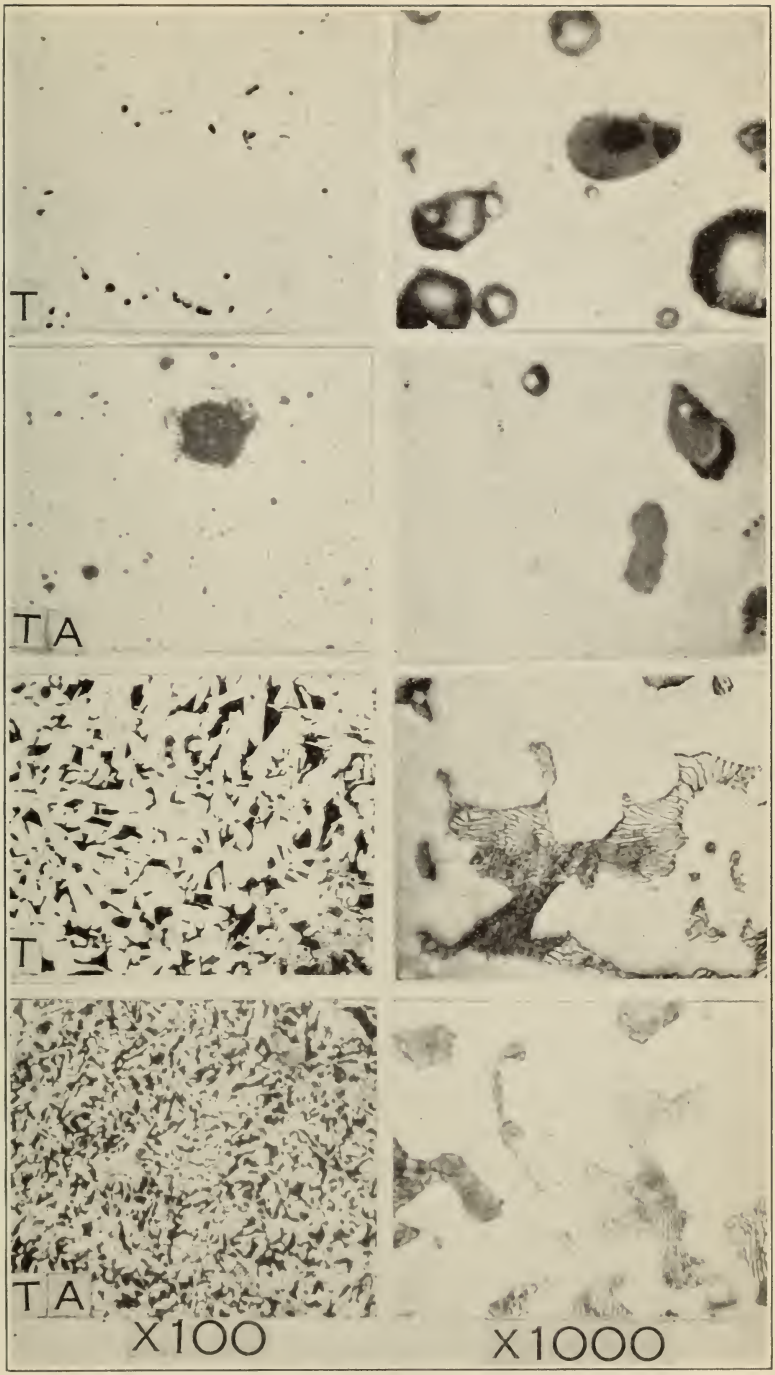

FIGURE 12.— *Inclusions in samples from overreduced heat 6699*

Letters indicate the time at which samples were taken during the progress of the heat. (See Table 2.) Specimens in upper half of figure in unetched condition. Specimens in lower half of figure etched in 2 per cent nital.

The specimens from samples "T" and "TA" were etched in a 2 per cent solution of nitric acid in alcohol in order to show the general structure. There were no appreciable differences in the microstructures of the steels before and after the aluminum addition.

6. CHEMICAL COMPOSITION

(a) METAL AND SLAG

The results of chemical analyses of the metal for the usual constituents and of the slag have been included in Tables 1 and 2.

The chief differences in the two types of heats, as shown by these data, are that the normal steels were inclined to melt down to, and maintain, in the early part of the heat, a carbon content which is distinctly lower than is the carbon at the corresponding stages of an overreduced heat. This is consistent with the idea that the normal heats are more highly oxidized than the overreduced heats.

(b) INCLUSIONS AND OXYGEN

Analyses were made of all samples for nonemtallic inclusions and for oxygen and nitrogen.[8] The results of these analyses are given in Tables 4 and 5.

[8] Analyses by H. C. Vacher, J. S. Acken, and E. H. Hamilton of the National Bureau of Standards.

TABLE 4.—*Analyses of normal practice acid electric furnace steels for inclusions, oxygen and nitrogen*

HEAT NO 6704

Specimen mark	Furnace additions preceding sample	Metal composition— C	Si	Mn	Al	Residue analysis: Location or type of sample	SiO_2	MnO	Al_2O_3	Equivalent O_2	Vacuum fusion analysis: Location or type of sample	O_2[1]	N_2[1]
		Per cent	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*
A	Melt down					Original pellets	0.002	0.001	0.001	0.001	Cleaned pellets	0.064	
						do	.004	Nil	.001	.002	Center of spiral	.032	0.007
B	Ore	0.12	0.07	0.10		Acid-washed pellets	.002						
						Pouring basin (spiral)	.010						
						Original pellets	.031	.003	.002	.019	do	.043	.006
C	Washed metal	.14	.05	.10		Acid-washed pellets	.034						
						Pouring basin (spiral)	.023						
						Original pellets	.048	.006	.003	.029	Pouring basin (spiral)	.017	.008
						Acid-washed pellets	.017		.001	.009	Spiral proper	.025	.008
D	Washed metal; Fe-Si, Fe-Mn.	.25	.40	.99		Pouring basin (spiral)	.008		.002	.005			
						Melter's count ingot	.006						
T		.25	.37	.69	N. d.[2]	Tensile test specimen	.022	.004	.003	.015	Tensile test specimen	.019	.008
TA	Al (in ladle)				0.011	do	.007	.001	.020	.015	do	.008	.008

HEAT NO. 6705

Specimen mark	Furnace additions preceding sample	Metal composition— C	Si	Mn	Al	Residue analysis: Location or type of sample	SiO_2	MnO	Al_2O_3	Equivalent O_2	Vacuum fusion analysis: Location or type of sample	O_2[1]	N_2[1]
A	Melt down					Original pellets	0.004	Nil	0.001	0.002	Cleaned pellets	0.077	
						do	.007	0.002	.001	.005	Center of spiral	.046	0.011
B	Ore	0.10	0.08	0.11		Acid-washed pellets	.008						
						Pouring basin (spiral)	.012						
						Melter's count ingot	.012						
						Original pellets	.028	.003	.002	.017	Spiral proper	.034	.009
C	Washed metal	.08	.08	.12		Acid-washed pellets	.029						
						Pouring basin (spiral)	.041						
						Melter's count ingot	.040						
						Original pellets	.024	.005	.003	.016	do	.022	.008
						Acid-washed pellets	.022						
D	Fe-Si, Fe-Mn	.20	.37	.77		Pouring basin (spiral)	.023						
						Melter's count ingot	.021						
T		.19	.35	.73	<0.005	Tensile test specimen	.026	.006	.004	.017	Tensile test specimen	.025	.010
TA	Al (in ladle)				.021	do	.001	.001	.042	.020	do	.015	.010

[1] These values represent total oxygen and nitrogen in the metal whether present as inclusions, in solution, or as free "blowhole" gases, except in the case of analyses of aluminum-killed specimens in which case the vacuum fusion method did not completely reduce Al_2O_3.

[2] N. d. indicates "not detected."

TABLE 5.—*Analyses of overreduced acid electric furnace steels for inclusions, oxygen and nitrogen*

HEAT NO. 6698

Specimen mark	Furnace additions preceding sample	Metal composition—				Residue analysis					Vacuum fusion analysis		
		C	Si	Mn	Al	Location or type of sample	SiO_2	MnO	Al_2O_3	Equivalent O_2	Location or type of sample	O_2[1]	N_2[1]
		Per cent	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*
A	Melt down					Original pellets	0.049	0.008	0.003	0.029	Cleaned pellets	0.067	
B	Ore	0.24	0.08	0.12		do	.026	.001	.001	.014	Spiral proper	.045	0.010
						Acid washed pellets	.012						
						Pouring basin (spiral)	.021						
						Melter's count ingot	.025						
C	Fe-Si	.12	.16	.20		Original pellets	.112	.003	.003	.062	Pouring basin (spiral)	.047	.009
						Acid washed pellets	.104		.003	.057	Spiral proper	.033	.011
						Pouring basin (spiral)	.044		.002	.024			
						Melter's count ingot	.036						
D	Ore			.16		Original pellets	.128	.009	.004	.072	Pouring basin (spiral)	.041	.009
						Acid washed pellets	.086		.001	.046	Spiral proper	.028	.008
						Pouring basin (spiral)	.050		.003	.028			
E	Fe-Mn	.27	.34	1.07		do	.021				Center of spiral	.021	.008
						Center of spiral	.026	.003	.003	.016			
						Melter's count ingot	.018						
T		.22	.40	.72	<0.005	Tensile test specimen	.007	.002	.004	.006	Tensile test specimen	.013	.008
												.011	.009
TA	Al (in ladle)				.027	do	.006	.002	.028	.017	do	.012	.008
												.007	.008

[1] See note 1, Table 4.

TABLE 5.—*Analyses of overreduced acid electric furnace steels for inclusions, oxygen and nitrogen*—Continued

HEAT NO. 6699

Specimen mark	Furnace additions preceding sample	Metal composition—				Residue analysis					Vacuum fusion analysis		
		C	Si	Mn	Al	Location or type of sample	SiO_2	MnO	Al_2O_3	Equivalent O_2	Location or type of sample	O_2[1]	N_2[1]
		Per cent	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*
A	Melt down					Original pellets	0.030	0.001	0.002	0.017	Cleaned pellets	0.053	
B	Ore	0.30	0.04	0.20		do	.077	.009	.003	.045	Center of spiral	.064	0.006
						Acid washed pellets	.032		.001	.033			
						Pouring basin (spiral)	.040						
						Melter's count ingot	.048						
C	Fe-Si	.16	.28	.20		Original pellets	.121	.005	.006	.069	Pouring basin (spiral)	.032	
						Acid washed pellets	.085		.004	.047	Spiral proper	.030	.008
						Pouring basin (spiral)	.034		.004	.020			
						Melter's count ingot	.042						
D	Fe-Mn	.26	.32	1.06		Original pellets	.012	.001	.001	.006	do	.017	.009
						Pouring basin (spiral)	.011						
						Melter's count ingot	.010						
T		.21	.30	.67	N. d.[2]	Tensile test specimen	.017	.005	.002	.011	Tensile test specimen	.015	.008
TA	Al (in ladle)				0.022	do	.002	.001	.033	.017	do	.011	.008

[1] See note 1, Table 4.

[2] N. d. indicates "not detected."

The determinations of the inclusions were made by the hydrochloric acid residue method. This method is based on the one described by Kichline [9] and by Oberhoffer and Amman [10] for the determination of alumina in steel. It was found that by suitable treatment of the nonmetallic residue left from the solution of the steel sample in hydrochloric acid (a treatment similar to that used by Oberhoffer and Amman in treating the residue obtained by their modification of the bromine method) a rather satisfactory determination of silica could be made in addition to that of alumina. The alumina determination is quite accurate. The silica determination by the hydrochloric acid method has been shown to be rather satisfactory when the nonmetallic inclusions are over 50 per cent silica; it probably gives a more correct value than does the Dickenson method,[11] if, as is often the case, the latter is applied with the use of a caustic soda wash for the residue. While it is also possible to secure very closely checking determinations of manganous oxide in the residues by this method, such values are generally in error on the low side, due to the solubility of manganous oxide in the acid solvent. However, in the present case it is the silica which is of chief interest in the inclusion analyses.

The method, in brief, consists in dissolving on the steam bath, a 50-g sample of the steel (chips if desired) in approximately 30 per cent hydrochloric acid, filtering, washing the residue finally with hot 3 per cent Na_2CO_3 to remove silicic acid, and then igniting if it is desired to determine total residue. The residue is then fused with $KHSO_4$ and the cooled fusion dissolved in dilute hydrochloric acid. Any undissolved material is separated by filtration, ignited, fused with Na_2CO_3 and dissolved in dilute hydrochloric acid. The combined solutions of the fusions are evaporated to dryness, the silica dehydrated and separated by filtration, ignited and corrected with hydrofluoric acid. Any residue from the silica volatilization is dissolved and combined with the filtrate from the silica separation. The solution is treated with H_2SO_3 to reduce any chromium and with nitric acid to oxidize the iron. Manganese, iron, and chromium are then separated from aluminum by pouring the solution into a sodium hydroxide solution, heating the solution to boiling and allowing it to stand and cool for two hours. The precipitate contains the manganese, which may be determined and calculated to manganous oxide in the inclusions. The filtrate contains the aluminum which is determined as the phosphate.

The oxygen and nitrogen in all samples were determined by the vacuum-fusion method, the solid samples being melted in vacuum at 1,600° C. in a gas-free graphite crucible and the evolved carbon monoxide and nitrogen determined gravimetrically and volumetrically, respectively. This method is considered to give correct values for nitrogen for all the samples from the four heats thus analyzed and also to give accurate results for the total oxygen content of all the samples except those final samples to which aluminum had been added. Oxygen determined by the vacuum-fusion method in samples,

[9] F. C. Kichline, "Note on the Determination of Aluminum Oxide and Total Aluminum in Steel," J. Ind. Eng. Chem., 7, pp. 806–807; 1915.

[10] P. Oberhoffer and E. Amman, "Ein beitrag zur bestimmung oxydischer einschlüsse in roheisen und stahl," Stahl und Eisen, 47, pp. 1536–1540; 1927.

[11] J. H. S. Dickenson, "A Note on the Distribution of Silicates in Steel Ingots," J. Iron & Steel Inst., 113, No. 1, p. 177; 1926.

such as these latter, is usually somewhat lower than the correct value due to the slow reduction of aluminum in this method.

One of the difficulties in making analyses which shall be representative of the oxygen present either as inclusions or in solution in a steel during the progress of a heat is the manner of taking the metal samples. The analytical samples from the four heats in question were taken as indicated in Tables 4 and 5. Directly after the melt down of the heat, the metal was too wild to permit pouring any solid samples. The only "A" samples, therefore, were pellet samples secured by pouring a spoonful of metal, freed from slag, through a

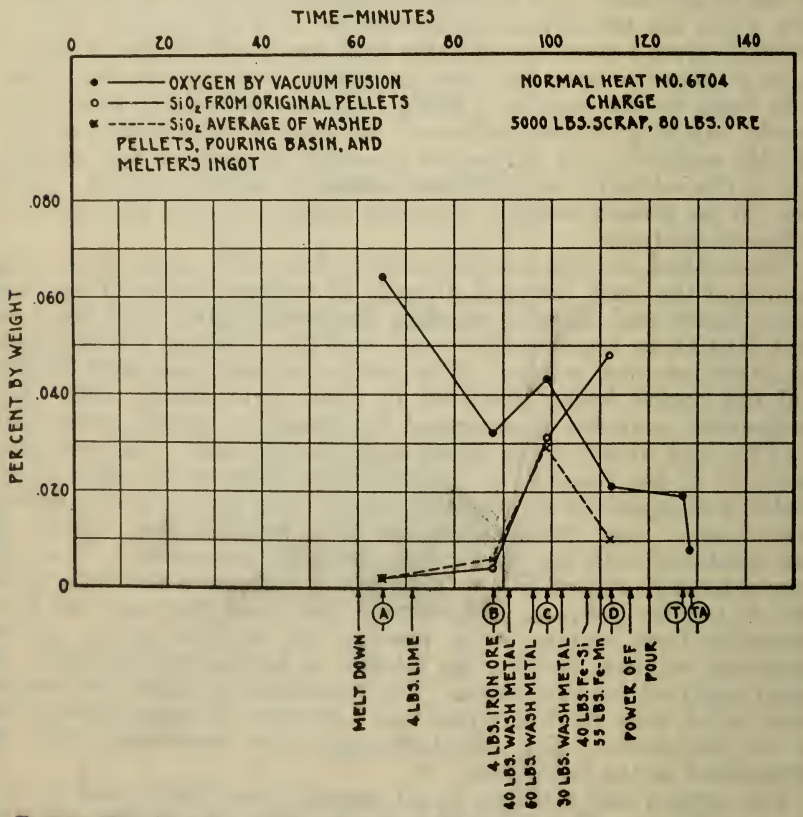

FIGURE 13.—*Change in oxygen and silica content during the progress of normal heat 6704*

heavy metal screen into water. Similar pellet samples were taken at each sampling period from each heat up to the time the metal was tapped into the ladle. In addition, there were available for samples the spiral castings from one kind of fluidity test and the hemispherical casting from another (melter's count). The analytical samples of the finished metal, without and with the addition of aluminum in the pouring ladle, were taken from the cast tensile test bars. The results of the vacuum-fusion method for oxygen analyses and of the residue method for silica analyses are shown graphically in Figures 13 to 16, inclusive, in addition to the tabulated data in Tables 4 and 5. The

tables include also nitrogen by the vacuum-fusion method and manganous oxide and alumina by the residue method, as well as a figure for total oxygen recovered as manganous oxide, alumina, and silica in the inclusions.

The analyses of the "A" samples by the vacuum-fusion method were made on the pellets, but only after very careful cleaning. The pellets were first treated with ammonium citrate solution, then with 1:2 hydrochloric acid, next with hot 3 per cent sodium carbonate solution to remove silicic acid, and finally they were heated at 900° C. in hydrogen for 15 to 20 minutes and allowed to cool in hydrogen.

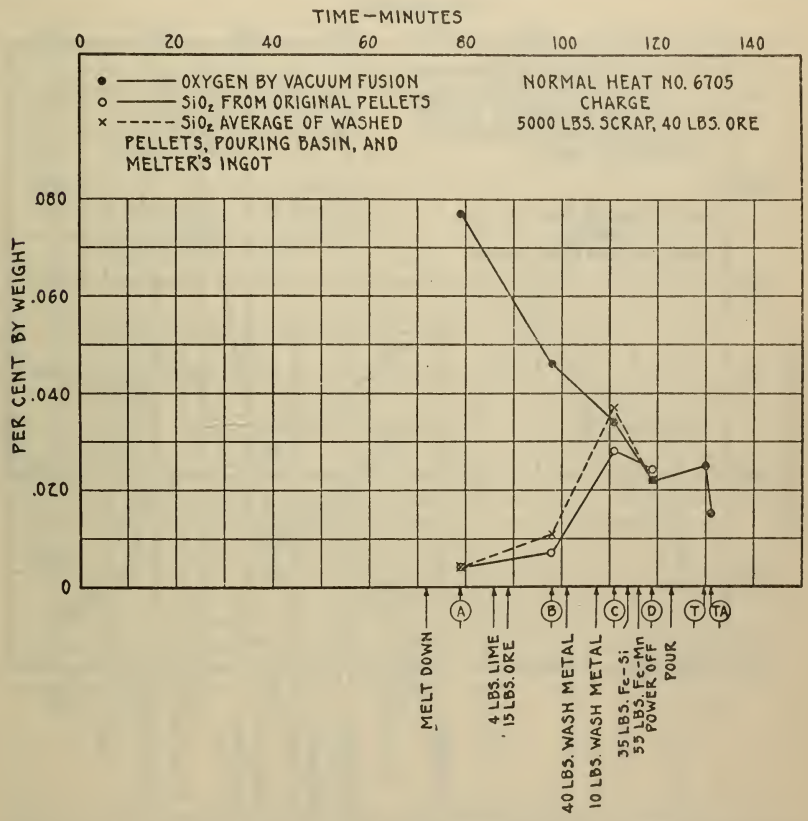

FIGURE 14.—*Change in oxygen and silica content during the progress of normal heat 6705*

The cool pellets were then used for the vacuum-fusion analyses with the reasonable assurance that they contained no surface oxide or slag. The samples designated as from "center of spiral" were solid pieces cut from the small reservoir of metal which fed directly into the spiral in the spiral fluidity casting, namely, from that portion of the spiral casting which shows uppermost in Figures 3 and 6. Samples designated "spiral proper" were taken as small sections of the spiral runner itself and those marked "pouring basin (spiral)" were from the larger reservoir of metal of the spiral casting, that portion which appears in the illustrations as the base of the spiral casting. The

values obtained for nitrogen by the vacuum-fusion method indicate no differences among the four heats nor do the nitrogen values show any appreciable variation throughout any heat. The heats all maintain and finish with a nitrogen content of between 0.008 and 0.010 per cent.

All four heats melted down with an oxygen content of from 0.06 to 0.08 per cent irrespective of whether considerable ore or no ore had been added with the charge. This oxygen content decreased quite steadily throughout all the heats until all four steels finished in the furnace with an oxygen content very close to 0.02 per cent.

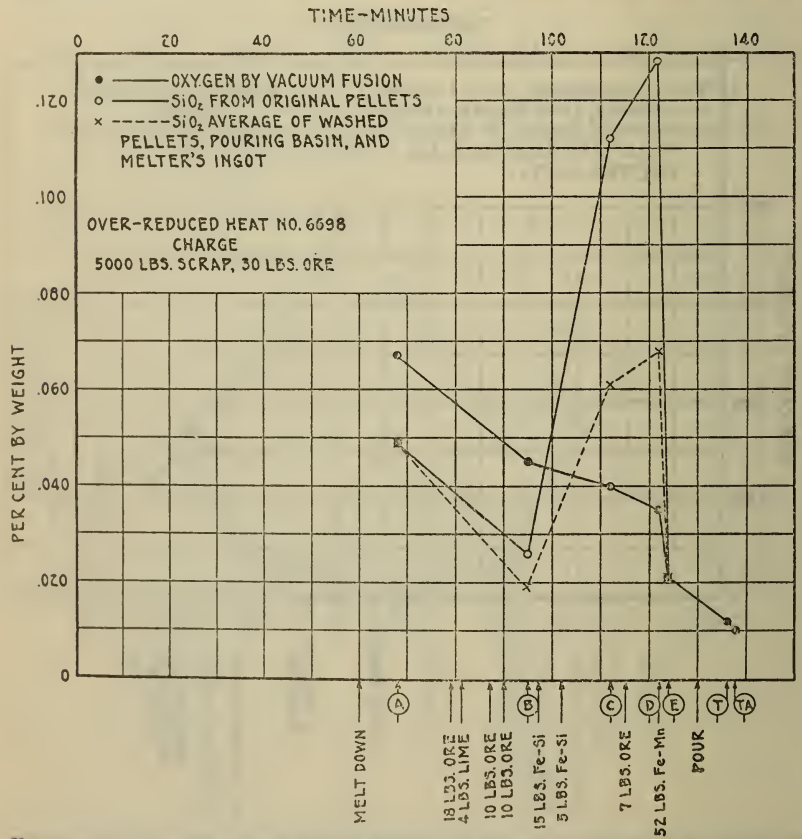

FIGURE 15.—*Change in oxygen and silica content during the progress of overreduced heat 6698*

There is thus no indication of any lower content of total oxygen at any stage or at the finish of those heats of the present series which, in the opinion of the steel plant operator, were overreduced.

The more complete analyses for the inclusions, that is, those including manganous oxide and alumina, were made only on the original pellet samples which were taken throughout the progress of the heats. By "original" pellet samples is to be understood the pellets just as they were recovered from pouring in water and without being subjected to any acid wash or other cleaning previous to their solution in the hydrochloric acid (residue method). Such pellets

obviously were somewhat rusted on their surfaces, but as the residue method is not used for determining oxides of iron, no error was thus introduced. It was apparent, however, that in certain samples there was a very appreciable concentration of silica on the surface of these pellets. There was a possibility that this might represent films of furnace slag remaining on the pellets or it might represent reaction at the surface of the pellets between excess silicon in the metal and air or steam surrounding the pellets during freezing when poured into water. Additional determinations of silica only were, therefore, made on samples from the pouring basin of the spiral casting

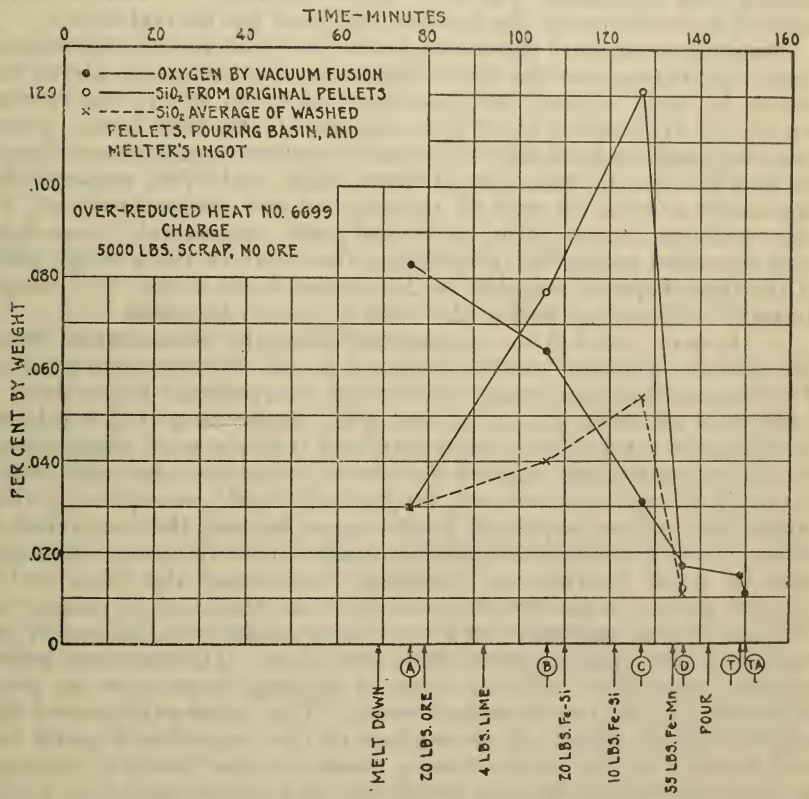

FIGURE 16.—*Change in oxygen and silica content during the progress of over-reduced heat 6699*

and from the melter's count casting as well as on additional pellet samples which were subjected to a preliminary short-time treatment (heating on the steam bath) in 1:2 hydrochloric acid, then removed, washed, dried, and the samples weighed for the residue analyses. The residue analyses showed little change in either manganous oxide or alumina throughout the progress of the heats, and no differences among the four heats with respect to these two constituents of the inclusions.

The results of the residue analyses for silica are possibly best presented in Figures 13 to 16. The silica indicated by analyses of

the original pellets is plotted separately. In addition, there is given a curve for silica representing the average of the results of analyses of acid-washed pellets and samples cut from the pouring basin and from the melter's count ingot.

It is readily seen that in the case of the two overreduced steels there is a very great discrepancy between the silica content of the original pellets and that of the other three types of samples. This marked difference does not occur in the two normal heats. It is also to be noted that the normal heats melted down very low in silica as compared with the overreduced heats indicating the prompt fluxing and cleansing action of larger amounts of ferrous oxide derived from the ore in the furnace charge of the normal heats.

Probably even more significant is the fact that in the overreduced heats the curves for the silica inclusions rise distinctly above the curves for total oxygen, but that they fail to do this in the normal heats. If one selects the "C" samples of the four heats, which most distinctly showed the differences in melter's counts (long counts, 52 and 72, for the two normal heats, 6704 and 6705, respectively, and short counts, 33 and 35 (average of two determinations), for the two overreduced heats, 6698 and 6699, respectively), one finds that the silica inclusions (considering the curve of the average silica of the three types of samples) in the normal steels at the "C" sample account for less than half of the total oxygen in the steel.

At the same point in the overreduced heats the silica content (from the similar "average" curve) accounts for all of the oxygen present. Further, at this same stage of the two overreduced heats there is present in the melt, silicon in very great excess over that combined as silica, the total silicon being 0.16 and 0.28 per cent, respectively. At the corresponding stage of the two normal heats the total silicon is only 0.05 and 0.08 per cent, respectively, and, consequently, relatively little silicon is present in the metal beyond that combined as silica. It is therefore reasonable to believe that the great difference already noted between the "average" silica and the silica of the original pellets in the overreduced heats at the time of taking the "C" samples is indicative of a very rapid oxidation of silicon at the surface of the liquid metal of these two heats. This occurred before pouring operations. At the time of pouring there were no great differences in the two classes of steels. This rapid oxidation of dissolved metallic silicon at the surface of the overreduced metal can well account for the shorter filming times or melter's counts, reported to be characteristic of such metal, the film formation which is observed being not the initial freezing of the metal but the formation and separation of a silica or silicate film. During the cooling of a normal steel which contains relatively very low concentrations of metallic silicon little or no film formation is to be expected until much lower temperatures are reached (longer time has elapsed) and iron oxide, or possibly iron silicates relatively very high in iron oxide, begins to form or separate from the liquid.

The composition of slags taken at the "C" stage of the four heats showed a higher content of silica for the overreduced heats than for the normal heats and a lower content of manganous oxide also. In the case of the overreduced heats a considerable excess of ferrosilicon was added before the "C" samples were taken while wash metal (low in silicon) only was added to the normal heats at this stage.

Just before the final samples were taken from all heats the ferromanganese additions were made. It is believed that ferromanganese rectified largely the effects of the overreduced heats by aiding in fluxing the inclusions high in silica. In the case of the normal heats the ferrosilicon was added about three minutes before the ferromanganese while in the overreduced heats the ferrosilicon was added about 20 minutes before the ferromanganese.

Consistent with the explanation in regard to the formation of refractory film are the melter's counts obtained when the "B" and "C" tests of the two overreduced heats were taken. At the time the "B" test of heat 6698 was taken the count was 43 seconds (Table 2), the total silicon was low and the residue analysis indicated that the "average" silica content of the metal accounted for only a small part of the total oxygen; that is, considerable iron oxide was present in the metal. Between the "B" and "C" tests this condition was radically changed. All the oxygen previously present as iron oxide reacted to form silica, metallic silicon was present in excess, and the analyses of the original pellets showed rapid surface oxidation of silicon, and the melter's count dropped from 43 to 33. In the case of heat 6699 the drop in melter's count between the "B" and "C" tests was still more striking, from 70 to 41, 34 and 36 (Table 2). This drop corresponds with the reaction of all the oxygen, remaining as iron oxide in the steel, to form silica and the presence of an excess of metallic silicon susceptible to rapid surface oxidation.

It is also to be recalled that it has already been noted that the addition of metallic aluminum to finished steels previously possessed of rather good fluidity (D, heat 6705 and E, heat 6698, Tables 1 and 2) very markedly reduced this fluidity as indicated by the cone and the spiral casting tests (F, heat 6705 and F, heat 6698, Tables 1 and 2) (figs. 4 and 5). That is, the presence of an excess of metallic aluminum may have a similar influence in reducing the fluidity of a steel and producing an overreduced condition by the formation of more refractory inclusions as does an excess of silicon.

If the presence of an excess of some reducing agent, as silicon or aluminum, with the accompanying necessary absence of iron oxide is indeed the characteristic of overreduced steels, and the nonmetallic film formation is the cause of the short count in the fluidity test, there still remains the need of offering some explanation of the manner in which this condition of the metal reduces the fluidity and causes difficulty in casting thin sections.

While it is true that the formation of a refractory oxide film on the surface of overreduced steel will cause that surface to appear brighter than the cleaner surface of a normal steel at the same temperature, because the emissivity of the oxide film is higher than that of a clean liquid iron surface, the actual temperature measurements made during the present investigation do not indicate any significant difference in temperature of the two sets of heats. Furthermore, it may be argued that there was actually little, if any, difference in the metal of the four heats at the time of finishing and that any distinction between normal and overreduced steel existed only before the finishing stages of these heats.

A higher emissivity of the surface of an overreduced steel does, indeed, mean that heat radiation from this surface is greater than from

a cleaner liquid metal surface and this difference may cause an appreciably greater rate in cooling of an overreduced steel. However, it is also possible that errors in comparing the temperatures of overreduced metal and normal metal have been made previously and because of the higher emissivity of the overreduced steel such heats have been cast at very considerably lower temperatures than the comparison normal steels with the consequent greater difficulty in running thin castings with the colder metal.

Quite aside from differences in pouring temperatures or in cooling rates, there is the possibility that the continuous silicate film formed on the liquid surface of an overreduced steel as it runs through a sand mold may cause a retardation of the flow of the metal. The silicate film may act as a membrane holding back the flow of a free surface of metal in a thin section. It may also cause what is practically a wetting of the sand of the mold faces by the iron inasmuch as the iron silicate film might be expected to be "wetted" by the steel and in turn it should wet the sand. Such a condition might well seriously retard the rate of flow of the liquid iron over the sand of a mold.

IV. SUMMARY AND CONCLUSIONS

A study of four heats of acid steel made in the electric furnace for steel castings, two of the heats being described by the steel foundry operators as "overreduced" steel and two heats as normal steels, failed to reveal any significant differences in temperature, rate of cooling, tensile properties, or microstructure as being the cause of the reported difficulty in pouring thin castings of the overreduced metal.

There were some differences in the steels during the progress of the heats as revealed by fluidity tests. These differences were that during the latter part of the heats of the two overreduced steels the melter's count (fluidity test) was much shorter (lower fluidity) than at the corresponding stage of the normal heats. Chemical analyses showed that at this same point all the oxygen, present as iron oxide in the overreduced steels, had reacted to form silica, and that there remained in the metal an excess of metallic silicon which very readily oxidized to a film of silica at the surface of the liqiud metal. This rapidly forming film of silica presumably accounts for the short fluidity count given by overreduced steels. It also may be the cause of incorrect measurement or judgement of temperature, since its emissivity is higher than that of a clean liquid steel surface. This may result in attempting to cast an overreduced steel at a temperature which is considerably lower than the temperature of a normal steel of the same apparent brightness at the surface.

The higher emissivity of the surface of an overreduced steel also should result in greater radiation losses as compared with a normal steel. It has not been possible to judge from the present work whether or not this factor is significant in its influence on the rate of cooling of such metal in practice and thus have an effect on fluidity.

It is suggested also that the silicate film formed in overreduced steels may act as a skin or membrane retarding the free flow of the liquid steel and even resulting in what is practically a wetting of the sand of the mold by the liquid overreduced steel.

If these types of steel are deoxidized with aluminum, shortly before pouring, the percentage elongation and the percentage reduction

of area of the finished product is appreciably lowered. It is shown that appreciable amounts of alumina remaining in the finished steel are responsible for the lowered ductility.

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